"FREE" CONSTITUENT QUARKS AND DILEPTON PRODUCTION IN HEAVY ION COLLISIONS *.

O.D. CHERNAVSKAYA, E.L. FEINBERG, I.I. ROYZEN

February 1, 2008

Lebedev Physical Institute of RAN, Leninski prospect 53, 117333 Moscow,Russia
e-mail: < *chernav@lpi.ru* >, < *feinberg@lpi.ru* >, < *royzen@lpi.ru* >

Abstract

An approach is suggested, invoking vitally the notion of constituent massive quarks (valons) which can survive and propagate rather than hadrons (except of pions) within the hot and dense matter formed below the chiral transition temperature in course of the heavy ion collisions at high energies. This approach is shown to be quite good for description of the experimentally observed excess in dilepton yield at masses 250 MeV $\leq M_{ee} \leq$ 700 MeV over the prompt resonance decay mechanism (CERES cocktail) predictions. In certain aspects, it looks to be even more successful, than the conventional approaches: it seems to match the data somewhat better at dilepton masses before the two-pion threshold and before the ρ-meson peak as well as at higher dilepton masses (beyond the ϕ-meson one). The approach implies no specific assumptions on the equation of state (EOS) or peculiarities of phase transitions in the expanding nuclear matter.

*This work is supported by the Russian Foundation for Basic Researches, grants No.'s 96-15-96798 and 00-02-17250.

INTRODUCTION

Few years ago, the experimental evidence has been obtained [1] that e^+e^- pairs (below referred as dileptons) with the invariant masses 250 MeV $\leq M \leq$ 700 MeV produced in course of heavy ion collisions at high energies are by far more numerous (up to a factor about $5 \div 7$), than what could be predicted by direct summing up the contributions of known mesonic resonance decays (CERES cocktail), although the similar treatment of dilepton yield in the proton-nucleus collisions was quite successful. Since then, many attempts have been made[2] to put forward a reasonable theoretical explanation of such a distinction. Generally, the most of these attempts were based on the thermodynamical approach [3] supplemented by some assumptions on the kinetics and in-medium properties of hadronic resonances (changes in their masses and widths [2, 4]) within the hot and dense matter (fireball) which was formed in course of the heavy ion collisions at high energies. It was demonstrated [2] that under a proper choice of resonance modifications (predominantly, of the ρ-meson width) a seemingly satisfactory agreement between the above experimental data and their theoretical treatment can be achieved. Unfortunately, the relevant models inevitably suffer from the well known underlying ambiguities - first of all, from the large extent of freedom in choice of EOS and of the in-medium particle mass operator. That is why their predictions are not undeniable and why the elaboration of some alternative approaches seems to be not out of place.

The approach we are to discuss below is based on a microscopic picture of the hot fireball evolution which necessarily implies the essential role of the massive constituent quarks [5](following R. Hwa [6], we call them below as "valons") at the certain stage of evolution. The notion of valon was quite fruitfully exploited at the early age of quark model and was almost forgotten after constructing the elegant QCD which makes it possible to deduce and predict many phenomena in terms of current (point-like) quarks and gluons. The attempts to embed valons rigorously into the framework of QCD as some quazibound color states of quarks and gluons were not proved to be successful [7], but, being physically very attractive, the notion of valon was exploited nevertheless for giving the qualitative motivations in favor of one or another statement. Among them, the attempts should be mentioned, first of all, to distinguish between the hadronic breakdown temperature [8] and the chiral symmetry restoration temperature by consideration either two successive phase transitions [9, 10] or gradual valonic mass decrease as the temperature rises, being above the former one [11].

The more detailed attempts to incorporate the valons as certain phenomenological entities has been made [12, 13] within the framework of the bag-model EOS of the nuclear matter. Two first order phase transitions were considered (instead of one within the conventional models) in course of the fireball expansion: first - from the short QGP phase to the intermediate one (chiral symmetry breaking at $T_{ch} \simeq 200$ MeV) which is rather short too - it lasts until quick cooling down to the Hagedorn temperature, $T_H \simeq 140$ MeV, is completed, and second - long and nearly isothermic transition (which is referred as mixed pion-valonic state by analogy with the conventional mixed QGP-hadronic state) from this phase to the short hadronic phase which ends by freeze-out at slightly lower temperature, $T_f \simeq 120$ MeV.

Being undoubtedly different, all these models (including the conventional ones) show

up one common feature: the (mixed) phase preceding the color confinement lasts much longer, than the other ones, irrespectively of peculiarities of a specific model. That is why one can reasonably believe that the substantial deceleration of expansion and corresponding prolongation of the pion-valonic phase is inherent not only in all versions of bag model - this qualitative effect is, most probably, the general and inevitable consequence of the necessity to meet the color confinement at low densities. In what follows we keep this pattern in mind as a guideline. Thus, within our approach, just the pion-valonic phase of expansion (not the QGP one) is expected to be responsible for the "extra dileptons" with low masses (over the CERES cocktail sample) seen at SPS: they can be really produced during this long phase in course of numerous successive collisions of particles within fireball. Being quite short, the hadronic phase can provide the resonance background (CERES cocktail) only.

The physical meaning of these phases in fireball evolution seems quite transparent [5] irrespectively of whether sharp or soft phase transitions take place as well as of the specific time profile of fireball temperature or of some other model-dependent peculiarities: the chiral symmetry breaking (restoration) and color confinement (deconfinement) are assumed to happen under essentially different thermodynamic conditions. The valon can be thought of as a quaziparticle in a sense that it absorbs the most part of strong color interaction to form (within a suitable range of temperatures and densities) the nearly ideal (color-screened) valonic gas that is equivalent in its physical manifestations to the gas of strongly interacting conventional (free) hadrons or QCD (point-like) quarks and gluons. One can deal with either of the above representations, but of these two options, the former is obviously by far more comfortable for the theoretical treatment. Indeed, within a medium of a density about the nucleon one (in which the nucleons bodies themselves would occupy the entire volume), the "equivalent" set of valon bodies (whose radius is supposed [14, 15] to be about three times smaller, than the nucleon one) would occupy about 10 % of the volume only. Therefore, even at the noticeably higher densities (say, at the density that is assumed to appear at the chiral phase transition - about twice as high as the nucleon one or about four times higher, than the nucleus density), a gaseous approach to the treatment of the valonic matter seems still reasonable. As usual, one has to pay for this simplification: a poorly determined entity - the cross section of valon-valon interaction - enters the relevant formulae inevitably. Below, a semi-quantitative approximation is suggested which makes it possible to overcome this unpleasant obstacle.

It is worthy to note that because of what is said above, the precise and complicated calculations are unnecessary even at those points where they really could be performed, when the problem we are interested in is considered. That is why the rather crude approximations we shall exploit below are suitable.

GENERAL DESCRIPTION OF THE APPROACH

The following picture of fireball evolution is adopted:

* After cooling down till the temperature $T = T_{ch}$, QGP fireball undergoes the rather quick phase transition[1] which results in formation of two-component (valonic and pionic)

[1]Nothing, except of temperature and baryon density prevents the point-like quarks and antiquarks

quaziideal gases in the equilibrium state[2]; the relative content of each species is regulated by the detailed balancing principle; the only interaction is accounted that converts valons $Q\bar{Q}$ into pions and vice versa.

** This state is maintained sufficiently long for producing dileptons numerously via the successive particle interactions. As for "macroscopic" patterns (longitudinal and transverse flows), they are subjected, as usual, to the relativistic thermo- and hydrodynamical treatment. What we need here of all that, is the estimate of duration of the pion-valonic phase. So long as, in the end, the necessity of color confinement at low densities is motivated above to be responsible for its prolongation, no reasons seem to be put forward for appearance of an essential difference in this respect between the suggested approach and conventional or bag model treatments. That is why the correspondent estimates given by the latter ones [12, 13, 17] will be quoted for orientation.

*** The mesonic resonances are expected to be nearly melted [18] over almost the entire duration of the pion-valonic phase in a sense that their effective widths are crucially influenced by the inverse mean free time $\bar{t}^{-1}$ which is undoubtedly larger, than the relevant intrinsic widths Γ_i [3]. That is why dileptons produced under such conditions in the reactions $\pi^+\pi^- \to e^+e^-$ and $Q\bar{Q} \to e^+e^-$ are to be treated reasonably as a kind of non-resonance multi-collision (transport) contribution (just what we are here to deal with) which should be added to dileptons originated from the mesonic resonance "normal" decays (CERES cocktail) at the final stage of expansion (when these resonances can survive. The heavier are the colliding nuclei and the higher is centrality of an observed collision, the more numerous should be these transport dileptons[4].

The general strategy of calculations looks as follows:

1. The total numbers of pions, N_π, and valons, N_Q and $N_{\bar{Q}}$, within fireball are linked by using the detailed balancing principle.

2. The rate of reactions $\pi^+\pi^- \to e^+e^-$ and $Q\bar{Q} \to e^+e^-$ is estimated as a function of M and N_π. Being multiplied by the entire duration of fireball expansion from the temperature T_{ch} to the temperature T_f, it gives the total yield of dileptons produced via pionic and valonic collisions.

3. N_π is linked to N_{ch}, the total number of charged hadrons coming from the fireball after freeze-out, and the general formula is adopted for comparing the results of calculations

---

to become "dressed" (i.e., to become the valons and antivalons, Q and $\bar{Q}$). That is why the valons are reasonably expected to appear at the proper conditions almost instantly.

[2]The pions are the only hadrons that have a good chance to survive within the medium at this stage because the binding energy of valons coupled to form a pion, $2\,m_Q - m_\pi \simeq 500$ MeV, substantially exceeds the temperature. Although the time of establishing the chemical equilibrium within fireball is, most probably, somewhat longer, than that of the chiral phase transition itself, it is comparatively short too [16].

[3]Since $T > T_H$, the mean free time (path) must be shorter or about 1 fm (the radius of valonic confinement or of hadronization); the effective width of each resonance thus is decreasing along with evolution of the intermediate phase to become finally $(\bar{t}^{-1} + \Gamma_i) \simeq 200$ MeV $+ \Gamma_i$.

[4]The dileptons coming from the processes of bremsstrahlung type do not practically contribute to the part of dilepton mass spectrum under discussion. Indeed, typical masses of bremsstrahlung virtual photons emitted by pions or u- and d-valons are wittingly lower, than m_π or m_Q, respectively, thus being, in any case, lower, than 300 MeV (in fact, the photons of much lower masses are noticeable only). As for heavier valons, yes, they could emit such a heavy photons (especially, c, b and t ones), but their relative concentration itself is by far too low and one can undoubtedly disregard the relevant dilepton yield.

and experimental data.

4. The obtained results are confronted to the available data for production of the low mass dileptons, as well as to the results of some conventional approaches.

DESIGNATIONS

$\frac{d\nu_Q^w}{dt}$ is the rate of the "white" $Q\bar{Q}$ collisions in which colors of Q and $\bar{Q}$ are cancelled to produce a color singlet state.
$\frac{d\nu_\pi}{dt}$ is the rate of $\pi^+\pi^-$ and $\pi^0\pi$ collisions.
$\frac{d\nu_Q^{wo}}{dt}$ and $\frac{d\nu_\pi^o}{dt}$ are the rates of collisions selected from the above ones in which the particles involved have necessarily the opposite (and non- zero) electric charges.
$\lambda\, =\, [\frac{N_Q}{N_{\bar{Q}}}]^{1/2}\, \simeq\, exp\,\frac{\mu_Q}{T}$, μ_Q being the chemical potential of u- and d-valons, denotes the valon fugacity.
$b\, =\, \frac{N_\pi}{N_Q+N_{\bar{Q}}}$.
$\bar{t}$ and τ denote the mean free time of particles within fireball and the duration of fireball cooling from the temperature T_{ch} to the temperature T_H, respectively.

CALCULATIONS

1. Being averaged over the particle distributions, the detailed balancing principle reads:

$$\nu_Q^w(T)\,\overline{\Omega_\pi}(T)\,\simeq\,\nu_\pi(T)\,\overline{\Omega_Q}(T) \tag{1}$$

where $\overline{\Omega_i}$ are the mean values of the corresponding final state phase spaces. Below, the binary reactions are to be considered only because $2\,\rightarrow\,4$ reactions are substantially suppressed by scarcity of the typical thermal final state phase space at $T\,<\,T_{ch}$, and 3 (or more) $\rightarrow$ *anything* reactions are rather rare events at the typical particle densities under consideration (however, see the discussion below). Besides, we restrict ourselves, for a while, with the two lightest flavors ($N_f\,=\,2$) because of the low concentration of s-quarks: their number is believed to be about [19] $(0,25\,\div\,0,5)\,exp[(\,m_{u,d}\,-\,m_s)/T]\,\simeq$ 10 % of the number of $(\bar{u}\,+\,\bar{d})$-quarks and thus the relevant corrections are obviously within the very accuracy of the suggested approach.

Since each antiquark of a certain color and flavor can encounter with the same probability λ^2 quarks and 1 antiquark ($2N_c$ species of each of them) and b pions for each of them, of which only 2 species are suitable to build a color singlet state,

$$d\nu_Q^w(T)\,=\,\frac{\lambda^2\,N_{\bar{Q}}}{(\lambda^2\,+\,1)(1\,+\,b)N_c}\,\frac{dt}{\bar{t}(T)} \tag{2}$$

Quite similarly, a π^0-meson encounters another π-meson with the probability $\frac{1}{(1+b^{-1})}\,\frac{dt}{\bar{t}}$, the total rate of $\pi^0\pi$ collisions being, therefore, $\frac{2N_\pi}{9(1+b^{-1})}\,\frac{dt}{\bar{t}}$ ($\pi^0\pi^\pm$ collisions) plus $\frac{N_{pi}}{18(1+b^{-1})}\,\frac{dt}{\bar{t}}$ $\pi^0\pi^0$ collisions); the rate of $\pi^+\pi^-$ collisions is obviously $\frac{N_\pi}{9(1+b^{-1})}\,\frac{dt}{\bar{t}}$. Of course, $\pi^+\pi^+$ and $\pi^-\pi^-$ collisions are out of the game in the detailed balancing principle equation (within the above approximation), since they never result in a two-valonic final state. Thus, for

the total rate of $\pi\pi$ collisions to be accounted one gets

$$d\nu_\pi(T) \,=\, \frac{7}{18}\,\frac{b\,N_\pi}{1\,+\,b} \tag{3}$$

The valonic and pionic phase spaces are

$$\overline{\Omega_Q}(T) \,\simeq\, 4(2S_Q+1)^2 N_c\,\overline{p_Q^2}(T) \quad \text{and} \quad \overline{\Omega_\pi}(T) \,\simeq\, (2I_\pi+1)^2\overline{p_\pi^2}(T), \tag{4}$$

respectively, where S_Q is the valonic spin and I_π is the pionic isospin, p_i are the valonic and pionic momenta, and N_c stands here instead of N_c^2, since only the color singlet part of the total phase space of two valons is allowed for. The straightforward averaging over the Boltzmann distribution gives for a particle of the mass m the mean value of its energy squared m

$$\overline{E^2(m,T)} \,=\, T^2\,[\,3\frac{\frac{m}{T}\,K_1(\frac{m}{T})}{K_2(\frac{m}{T})}\,+\,12\,+\,\frac{m^2}{T^2}\,]$$

where $K_{1,2}$ are the corresponding Bessel functions. The CMS value of $\overline{p_\pi^2}$ ($\overline{p_Q^2}$) of each particle in the pionic (valonic) final state is obtained obviously by insertion into this expression $m \,=\, m_Q$ ($m \,=\, m_\pi$) and subtraction m_π^2 (m_Q^2). Within the temperature range we are interested in, the ratio of these values varies slowly and it (namely, the mean value of pionic momentum squared to that of the valonic one) equals to $\simeq 2$ at the temperature $\bar{T} \,\simeq\, 160$ MeV which will be exploited in what follows as certain effective mean temperature instead of the current one. Making use of the above designations and combining eq's. (1) - (4), we obtain

$$b \,\simeq\, 0,6\,\frac{\lambda}{(\lambda^2\,+\,1)} \,\leq\, 0,3 \tag{5}$$

Since the fraction of "big" pions (as compared to "small" valons) is relatively small (at the reasonable value of λ, $\lambda \,\simeq\, \sqrt{3}$, that refers to $\mu_Q \,\simeq\, 80$ MeV, one has $b \,\simeq\, 0{,}24$), the motivation in favor of applicability of the gaseous approximation given above for the purely valonic medium remains valid. It is worthy to note also that this chemically equilibrium ratio of valons and pions corresponds to what would be obtained, if they were considered as being the ideal non-interacting gases. This fact enables, at least, to be sure that the rather crude and idealized gaseous approach to the problem under consideration is not controversial.

2. The rates of "white" collisions with zero total electric charge which can produce dileptons via the virtual photon intermediate state are estimated quite similarly:

$$d\nu_Q^o \,=\, 0,5\,d\nu_Q \quad \text{and} \quad d\nu_\pi^o \,=\, \frac{b}{9(1\,+\,b)}\,\frac{dt}{\bar{t}} \tag{6}$$

It is easy to check that the probability dW/dM of a two particle collision with the invariant mass (the total energy in their CMS) M is (in the ideal Boltzmann gas approximation[5]):

$$\frac{dW}{dM} \,=\, \frac{M}{8}\,\frac{\int_M^\infty e^{-\xi/T}d\xi\int_0^{\sqrt{(\xi^2-M^2)(1-\frac{4m_i^2}{M^2})}}(\xi^2\,-\,\eta^2)d\eta}{[\int_0^\infty p^2 e^{-\sqrt{p^2+m_i^2}/T}dp]^2} \tag{7}$$

[5] There is no reason to refine it by taking into account the Bose and Fermi statistics of pions and valons, respectively, in face of the low accuracy and specific kinematical selection (see below) of the available experimental data.

where $i = Q, \pi,$ ξ and η denote the sum and difference of colliding particle energies, respectively[6].

3. To compare the above approach straightforwardly with the experimental data on dilepton production, one should to link the numbers of pions and valons within fireball and the number of the observed charged particles. This relation is suggested to be as follows:

$$N_{ch} \simeq \frac{2}{3} N_\pi + 2N_{\bar{Q}} + 0,4\, N_B \tag{8}$$

where

$$N_B = \frac{1}{3}(\lambda^2 - 1) N_{\bar{Q}}^{u+d} \simeq \frac{1}{3}(\lambda^2 - 1) N_{\bar{Q}}$$

is the fireball total baryon number and, thus, 0,4 N_B is approximately equal to the proton outcome from the fireball (in the accordance with the approximate ratio of protons and neutrons in the heavy ion collisions). Eq.(8) implies also that, in course of *thermally equilibrium* hadronization, the number of decoupled pions emerged from the fireball is nearly equal to the number of pions which were coupled within it and that each $Q\bar{Q}$ pair produces about 2 charged pions (actually, about three of them, the third being neutral).

Now, combining eq.s (5 - 8), we come to the basic formula for the excess in dilepton yield which is to be compared to the observations:

$$\frac{1}{N_{ch}} \frac{dN_{ee}}{dM} \simeq \frac{0,1\,\lambda^2\,(1 + 0,6\lambda + \lambda^2)^{-1}}{4,7 + \lambda + 0,33\lambda^2}\ \frac{\tau}{\bar{t}}\ [\, \frac{dW_{\pi\pi}}{dM} \frac{\sigma_{\pi\pi\to ee}}{\sigma^{tot}_{\pi\pi}} + 4\, \frac{dW_{Q\bar{Q}}}{dM}\, \frac{\sigma_{QQ\to ee}}{\sigma^{tot}_{Q\bar{Q}}}$$

$$+ \beta \times (the\ previous\ item,\ where\ Q_s\ stands\ instead\ of\ Q \equiv Q_{u,d})\,], \tag{9}$$

where $\sigma_{Q\bar{Q}}$ stands for the half-sum of the cross sections of $Q_u\bar{Q}_u$ and of $Q_d\bar{Q}_d$ annihilation into e^+e^-, $\sigma^{tot}_{\pi\pi}$ and $\sigma^{tot}_{Q\bar{Q}}$ stand for the corresponding total cross sections, and β accounts the relative rate of strange valon collisions, $\beta \simeq 0{,}1$ (see above). The relative effectiveness of the latter ones in dilepton production is still $\simeq$ 1,7 times lower[7], thus being about 6 % of the light quark one. That is why below the strange valon contribution is neglected. Of course, eq.(9) could be reformulated to look more traditionally (for the latter see [20]), making use the above relations and well known definition $\sigma_i^{tot}\bar{t}_i sqrt2 \simeq n_i^{-1}$, where n_i is the number density of ith particle species and σ_i^{tot} and $\bar{t}_i$ are the relevant cross section and mean free time, respectively. The chosen way of description is preferred here deliberately to avoid unnecessary complications. Moreover, its physical meaning seems more transparent, whereas the drawbacks of two ways of description are essentially equivalent (poorly defined $\pi\pi$ and $Q\bar{Q}$ total cross sections in the one given here and equally poorly defined corresponding in-medium ρ-meson electromagnetic formfactor which would enter inevitably the usually exploited formulae).

Two general results can be deduced from eq.(9) right away, before going into more detailed calculations. First, the mean number of successive interactions of a particle over

[6]The nominator here is nothing else than the product of the momentum distributions of two independent particles in the CMS of a small volume dV (where they are assumed to be spherically symmetrical) integrated with the factor $\delta[(p_1 + p_2)^2 - M^2]$, whereas the denominator accounts the normalization.

[7]This coefficient is resulted as the interplay of two factors: the ratio of quark electromagnetic charges squared, $(e_u^2 + e_d^2)/2\, e_s^2 = 2,5$, and the ratio $\sigma^{tot}_{Q\bar{Q}}/\sigma^{tot}_{Q_s\bar{Q}_s}$ estimated from comparison of πp and Kp cross sections to be nearly equal to 1,5.

the fireball evolution time, $\tau/\bar{t}$, is the only factor on the right-hand side of eq.(9) which depends on N_{ch}: $\tau \sim V \sim N_{ch}$ and $\tau \sim V^{1/3} \sim N_{ch}^{1/3}$ in the limiting cases of one-dimensional (longitudinal) and three-dimensional (spherical) expansion of the fireball, respectively (V is the fireball volume at the freeze-out temperature); thus, eq.(9) admits apparently the trend $N_{ee} \sim N_{ch}^2$ observed in the SPS experiments [21]. Second,the predicted excess in dilepton yield is almost insensitive to the choice of valon chemical potential within the range $0 \leq \mu_Q \leq 80$ MeV, since the corresponding variation of the λ-dependent factor on the right hand side of eq.(9) does not exceed 20 % [8].

The most vulnerable point of the formula (9) is the ratio of the above cross sections. It can be estimated within the framework of the following reasoning. The resonance irregularities (mostly, the ρ-meson one) in the cross section of dilepton production and in the total one are expected to be of the similar (the same within VDM) shape [22] and cancel each other substantially. That is why the background contributions (namely they are meant under the letter σ below) are to be compared only. Thus,

$$\sigma_{\pi\pi\to ee} \simeq \frac{4\pi\alpha^2}{3M^2} \quad \text{and} \quad \sigma_{Q\bar{Q}\to ee} \simeq \frac{10\pi\alpha^2}{27M^2}$$

. The total cross sections of $Q\bar{Q}$ and $\pi\pi$ interactions can be estimated, obviously, only in terms of plausibility and similarity to the known hadronic ones. We assume that, in spirit of the suggested approach, each of u and d valons (antivalons) interacts (strongly), as if it were "1/3 of the proton" (antiproton). Since the cross section of $p\bar{p}$ interaction [23] exhibits almost no resonance structure and can be fitted pretty well (at not too high CMS energies E_c) by the simple phenomenological formula[9]

$$(\,\sigma_{p\bar{p}}(E_c)\, - 40\,\text{mb})\, \simeq \,\frac{24\,\text{mb}}{\sqrt{\frac{E_c}{2\,m_p}\, - \,1}}, \tag{10}$$

one can expect that the corresponding cross section of the light valon-antivalon interaction respects approximately the formula

$$(\,\sigma_{Q\bar{Q}}(M) - \,9\,\text{mb})\, \simeq \,\frac{5,4\,\text{mb}}{\sqrt{\frac{M}{2\,m_Q}\, - \,1}} \tag{11}$$

where the $Q_{u,d}\bar{Q}_{u,d}$ cross section at the CMS energy $M = E_c/3$ is estimated to be about 0,22 (instead of 1/9) of the $p\bar{p}$ one at the CMS energy E_c, taking into account $\simeq$ 50 % shadowing in the $p\bar{p}$ interaction[10].

[8] However, at lower energies (AGS, SIS), when this potential is expected to be considerably higher, its influence should result in quite observable (about 2 times) diminishing the dilepton excess in collisions of the same nuclei as compared to the SPS one. At the same time, it should be noted that similar effect comes from decrease of the ratio $\tau/\bar{t}$ at too low energies, when the fireball initial temperature $T_i < T_{ch}$.

[9] This formula corrected by multiplication of its right-hand side by the factor $(E_c/2m_p)^{-0,4}$ (which is of no importance within the energy range of our interest here) smoothly interpolates between the threshold behavior of the total $p\bar{p}$ cross section and its high energy parametrization [23] motivated by the Regge approach.

[10] This qualitative estimate is emerged from the observation that πp and pp total cross sections at the relevant energies are more likely related as 5:6 [23], than as 2:3, what would be expected, if no shadowing were at all. By the way, eq.(11) is coordinated pretty good with the (also qualitative) estimate that $Q\bar{Q}$ total cross section at CMS energy of several GeV should be of the order of confinement radius squared, i.e., $\simeq 1\,\text{fm}^2 \simeq 10$ mb.

This way of reasoning is not applicable immediately for linking the shapes of the $p\bar{p}$ and $\pi^+\pi^-$ total cross sections, first of all, because the former reaction is exothermic[11] (just like the $Q\bar{Q}$ one), whereas the latter one is not, and therefore, the above cross sections differ essentially in their threshold behavior. Nevertheless, the available experimental data show up unambiguously a general trend of all the known hadronic cross sections (apart from their resonance structure, i.e., averaged with respect to it - namely, of their background components which are just relevant) to increase gradually toward the threshold (except of, maybe, a very narrow domain in the close vicinity of the threshold). Compiling the data, one can conclude that these cross sections show up a $(2 \div 3)$ time decrease as the CMS energy increases by about 1 GeV above the threshold, and that they approach the almost constant values as the energy exceeds substantially the sum of the interacting particle masses. We seem reasonable to assume that the same is qualitatively true for the background component of the $\pi^+\pi^-$ cross section as well. That is why the following formula can be proposed:

$$(\sigma_{\pi\pi}(M) \, - \, \sigma_0 \,) \, \simeq \, \frac{3 \, \sigma_0 \Delta}{\sqrt{\frac{M}{2 \, m_\pi} \, - \, 1} \, + \, \Delta} \tag{12}$$

where $\sigma_0 \, \simeq \, (10 \div 15)$ mb is the high energy value of $\sigma_{\pi\pi}$ and $0,2 \, \leq \, \Delta \, \leq 1$, a some low value of Δ from this interval seeming rather more suitable because of the relatively small pion mass.

4. After insertion of eq.s (11 - 13) into the basic eq.(9), we are almost ready for comparing the approach with the data. What remains to be done is to adapt the formula (7) to the specific conditions of the measurements, i.e. to take into account that the leptons, e^+ and e^-, with transverse momenta $p_T > \, 200$ MeV have been selected only in all the data and that the further selection of the data into two groups incorporating the events with dilepton total transverse momenta 200 MeV $< \, q_T < 500$ MeV and $q_T > 500$ MeV, respectively, has been made. These restrictions are allowed for approximately: the limits of integration over ξ in eq.(7) are chosen to account the above conditions in the average (i.e., these limits correspond to a "typical dilepton" built up of two leptons, whose momenta are averaged over their relative directions and over their absolute values). As a result,

$$max \, [\, M, \, p_T \sqrt{6} \, \simeq \, 0,5 \, \text{GeV} \,], \quad p_T = \, 0,2 \, \text{GeV},$$

stands instead of M for the lower limit and

$$\sqrt{M^2 + \, \frac{3}{2} q_T^2}, \quad q_T = \, 0,5 \, \text{GeV},$$

stands for the upper (lower) limit for the events with $q_T < \, 0,5$ GeV $\;$ ($q_T > \, 0,5$ GeV).

Below, the results of the suggested approach are compared to the experimental data and to the theoretical predictions obtained within the frameworks of some conventional

[11] That is why the simplest interpolation of the form $\sim \, (E_c \, - \, 2 \, m_p)^{-\frac{1}{2}}$ fits its cross section fairly well.

theoretical approaches.

DISCUSSION AND CONCLUDING REMARKS.

At first sight, a doubt could be expressed that the valons play an essential role in producing the dileptons with masses $M \leq 2m_Q \simeq 660$ MeV which are just of the primary interest here, since they do not produce these dileptons directly. However, it is not correct: they do play this role because they directly affect the number of pions within the fireball and the number of charged particles in the final state, and, therefore, their influence on the ratio of dileptons to charged particles is quite unambiguous.

Unfortunately, we can not extract from our results the direct information about the duration of fireball expansion τ and about the mean free time $\bar{t}$ separately because dilepton yield is proportional to their ratio only. The curves presented in Fig's. 1 and 2a,b are obtained provided that $\tau/\bar{t} = 20$ or 30 for free pions ($m_\pi = 140$ MeV) or "in-medium" pions ($m_\pi = 100$ MeV), respectively. At the same time, the quadratic growth of the total dilepton yield as compared to the charged particle one, $N_{ee} \sim N_{ch}^2$, that was drawn [21] from the CERES data witnesses in favor of the predominantly longitudinal fireball expansion at the SPS energies. The well known estimates predict in this case a rather long expansion time [13, 17]. If one adopts a reasonable estimate for the mean free time, $\bar{t} \simeq (0,7 \div 1)$ fm, then the duration of pion-valonic phase (which is nearly equal to the entire duration of fireball expansion) is $\tau \simeq (15 \div 20)$ fm or $(20 \div 30)$ fm for free and in-medium pions, respectively. These values are compatible with what was predicted, the latter seeming somewhat more preferable.

At the same time, due to a considerable enhancement of pressure within the fireball along with increase of its energy density predicted in the framework of the hydrodynamical model, the role of transverse flow increases too, and thus, the three-dimensional pattern of fireball expansion is expected to become substantially more pronounced in RHIC and LHC collisions. As a result, a certain modification in the functional form of the above correlation is expected to be observed, the 2th power there being gradually decreased toward the 4/3th one (which refers to the spherical expansion). Thus, at RHIC, one can expect a noticeably slower rise of the excess in dilepton yield over the CERES cocktail sample, than it would be predicted by careless extrapolation of the longitudinal expansion models (say, than $\simeq$ 4,5 times as compared to SPS, if one assumes that $N_{ch} \sim E_c^{1/2}$).

Within the suggested approach, the three-particle collisions were neglected. This approximation can be justified, only if the mean interaction time ($\simeq$ the particle size) is much smaller, than the mean free time ($\simeq$ the mean free path). One has to agree that the above estimate of reasonable value of the mean free time, $\bar{t} \simeq (0,7 \div 1,0)$ fm, does not answer this requirement completely even for the valons of the size about 0,3 fm. A typical diagram that refers to three-particle collision is shown in Fig. 3. Intervention of a third particle (labelled as 3) results, apparently, in some dispersion of dilepton mass around its only value which would be prescribed by the energy conservation low, if only two particles were collide. In turn, it results in smoothing the irregularities (kinks, dips or bumps), if they are inherent in the dilepton mass spectrum predicted by two-particle collision kinematics. In particular, the dip in the spectrum before the two-pion threshold obtained in the two-particle collision approximation, see Fig. 2a, could be flatten, to

some extent, by this smoothing. However, the relevant corrections are hardly sufficient to level this dip completely - we mean a quite probable minimum also seen there in the data specially selected to emphasize the contribution of pion-pion collisions.

At the same time, Fig. 1 shows that occurrence of a noticeable dip before $2m_\pi$ threshold is apparently predicted in the entire bulk of data, if the in-medium pion mass equals to the free one, whereas almost no visible dip is predicted, if an effective lowering of this mass is qualitatively allowed for by taking it equal to 100 MeV. That is why the essential refinement of the data within this mass region is asked anxiously because it can provide the valuable information on properties of dense and hot matter that might occur even more important, than the dilepton yield itself. In particular, it can be correlated to the properties of the chiral transition. As for the properly selected events, $q_T \leq 500$ MeV (see Fig. 2), we would like to point out again that this dip is quite apparently predicted by either of the above versions of the theoretical approach suggested, in contrast to the conventional ones. Again the allowance for a some decrease of the in-medium pion mass seems fruitful (although three particle interaction could be responsible too (see above) for a slight shift to the left of the minimum suggested by the data from the position predicted by the free pion mass version of the approach presented).

The predicted yield of dileptons with $M_\rho \leq M \leq M_\phi$ looks slightly overestimated, see Fig.s 1, 2. However, this excess (if it can be taken seriously into consideration in face of too poor accuracy of the data) which is undoubtedly due to $Q\bar{Q}$ annihilation may occur rather illusive: in particular, at the ϕ-meson peak, the experimental points are situated even slightly lower, than they are expected to occur according to the estimate of the prompt resonance (CERES cocktail) contribution itself, what seems unreasonable. This disparity can be taken as a hint that something here may suffer from a systematical error. If it is the case, then the agreement between our predictions and the data is improved irrespectively of what - data or CERES cocktail - is to be corrected, since what we have calculated is just the expected excess in the observed dilepton yield over the CERES cocktail sample. At still higher dilepton masses, both the data and our results (unlike the other ones) show up the quite compatible excess over this sample, see Fig. 2b, which is undoubtedly due to $Q\bar{Q}$ annihilation.

An advantage of the suggested approach is that its physical sense and internal structure are very transparent and opened for discussion, tracing and corrections, since no complicated generators are involved: almost all the calculations are quite simple for being performed approximately by hands.

Summing up what was said above, we conclude that the low-mass spectrum of dileptons produced in course of the heavy ion collisions can be understood in quite natural way in terms of the pion-valonic contents of the expanding hot and dense matter (fireball) below the chiral transition temperature. The above consideration showed, however, that dilepton production is affected by a number of factors and that some of them could be estimated rather semi-quantitatively. Thus, we are supplied again with an insight on fruitfulness of using the notion of valon, although the suggested evidences in favor of its right to be acknowledged as a real physical object are still far from being decisive.

The authors are indebted to N.G. Polukhina for the valuable help in composing the figures.

References

[1] G. Agakichiev et al. (CERES Collaboration), Phys. Rev. Lett. 1995, vol. 75, p. 1272; Phys. Lett., 1998, vol. B422, p. 405.

[2] R. Rapp, Nucl. Phys. 1999, vol. A661, p. 33c, and ref.s therein.

[3] E.L. Feinberg, Nouvo Cim. 1976, vol. 34, p. 391; Sov. Phys. Uspecki, 1983, vol. 26, p. 1, and ref,s therein.

[4] B. Friman, Nucl. Phys. 1996, vol. A610, p. 358c. and ref.s therein.

[5] E.L. Feinberg, in: "Relativistic Heavy Ion Collisions", Ed. L.P. Chernai, D.D. Strottman, World Scientific, 1991.

[6] R. Hwa, Phys. Rev. 1979, vol. D20, p. 2838.

[7] K.G. Wilson, Phys. Rev. 1974, vol. D10, p. 2245.

[8] R.C. Hagedorn, Suppl. Nuovo Cim. 1965, vol. 3, p. 147.

[9] O.K. Kalashnikov, V.V. Klimov, Phys. Lett. 1979, vol. B88, p. 328.

[10] E.V. Shuryak, Phys. Lett. 1981, vol. B107, p. 103.

[11] A.V. Bochkarev, M.E. Shaposhnikov, Nucl. Phys. 1986, vol. B268, p. 220.

[12] J. Cleymans, K. Redlich, H. Satz, E. Suhonen, Z.Phys. 1986, vol. C33, p. 151; D.V. Anchishkin, K.A. Bugaev, M.I. Gorenstein, Z.Phys. 1990, vol. C45, p. 687; S.P. Baranov, L.V. Fil'kov, Z.Phys. 1993, vol. C57, p.149.

[13] O.D. Chernavskaya, E.L. Feinberg, in: "Hot Hadronic Matter: Theory and Experiment", Ed. J. Letessier, J. Rafelski, Plenum Press, 1995; J. Moscow Phys. Soc. 1996, vol. 6, p. 37.

[14] V.V. Anisovich et al., Sov. Phys. Uspecki 1984, vol. 4, p. 553.

[15] B.L. Ioffe, V.A. Khoze,: "Hard Processes", vol. 1: "Phenomenology, Quark-Parton Model", North Holland, Amsterdam, 1984.

[16] U. Heinz, Nucl. Phys. 1999, vol. A661, p. 140c.

[17] R. Stock, Nucl. Phys. 1999, vol. A661, p. 282c, and ref.s therein.

[18] V.L. Eletsky et al., Eur. J. Phys. 1998, vol. A3, p. 381; Nucl. Phys. 1999, vol. A661, p. 514c.

[19] J. Sollfrank et al., Nucl. Phys. 1998, vol. A638, p. 399c.

[20] G. Gale, J. Kapusta, Phys. Rev. 1987, vol. C35, p. 2107.

[21] J. Stachel, Talk at the CERN Seminar, February 10, 2000.

[22] F.M. Renard, "Basics of Electron-Positron Collisions", Chapter 6, Editions Frontieres, Giv sur Yvette, France, 1981; see also H. Joss, Proc. of the Hiedelberg Int. Conf. on the Elementary Particles, Amsterdam, 1967.

[23] Phys. Rev. 1996, vol. D54 (Review of Particle Physics), pp. 191-195.

[24] R. Rapp, Talk at the Int. Conf. Quark Matter '99, Torino, Italy, 10-15 May, 1999.

FIGURE CAPTIONS

Fig. 1. Our results (bold solid and bold dashed lines refer to $m_\pi = 140$ MeV, $\tau/\bar{t} = 20$ and $m_\pi = 100$ MeV, $\tau/\bar{t} = 30$, respectively; $\sigma_0 = 10$ mb, $\Delta = 0{,}2$ GeV) are confronted to the entire bulk of CERES dilepton data [1] and predictions of thermal dilepton calculations quoted from ref.[2, 24]

Fig. 2. The same as in Fig. 1 for the two q_T selected groups of the data.

Fig. 3. A typical diagram of three-particle collision. It shows that intervention of the 'third" particle can affect the mass of produced dilepton pair to shift it up or down. In particular, this mass can occur below the physical threshold of the corresponding two-particle (1 + 2) reaction. A very likely minimum before the two-pion threshold seen in Fig. 2a is indicative for the conclusion that contribution of three-particle collisions to dilepton yield is rather small.